A&A manuscript no.
(will be inserted by hand later)

Your thesaurus codes are:
06(13.25.5; 08.09.2 GS1826-24; 08.14.1)

ASTRONOMY AND ASTROPHYSICS
2.4.1996

OSSE observations of positron annihilation in the galactic plane

R.L. Kinzer[1], W. R. Purcell[2], W. N. Johnson[1], J. D. Kurfess[1], G. Jung[3], and J. Skibo[1]

[1] Naval Research Laboratory, Code 7650, Washington DC 20375, USA
[2] Department of Physics and Astronomy, Northwestern University, Evanston IL 60208, USA
[3] Universities Space Research Association, Washigton, DC 20024, USA

Received ; accepted

Abstract. OSSE has measured the galactic longitude distribution of both the 511 keV annihilation line radiation and the three-photon positronium continuum within $\sim 40°$ of the center. They have similar shapes, with a composite longitude distribution well represented by an $\sim 11°$ FWHM Gaussian central bulge together with a possible broad disk component comprising as much as 15% of the integral flux between 40° and 320° longitude. Contributions from one or more discrete source(s) at or near the center with total annihilation radiation (line plus continuum) intensities of up to $\sim 4 \times 10^{-4}$ photons cm^{-2} sec^{-1} (2σ upper limit) are compatible with the observed distribution. The best estimate of the positronium fraction is 0.97 $\pm$0.03. No evidence for variation in the positronium fraction is observed.

Key words: galaxies: Milky Way – Galaxies: center – ISM: general – gamma rays: observations

1. INTRODUCTION

Positron annihilation is important in astrophysics because it provides unique signatures of the nature and state of matter from which it emanates, and because it occurs in the galaxy with sufficient intensity to be detectable at Earth. This radiation was first unambiguously detected through its 0.511 MeV line radiation from sources outside the solar system during observations of the galactic center in balloon observations by Johnson & Haymes (1973); it has since been observed from the galactic center region by numerous balloon and satellite-borne experiments.

Positrons can be copiously produced by a number of sources which are important in our galaxy, including: cosmic ray interactions in the interstellar medium, pulsars, β^+ decay products from radioactive nuclei (e.g. ^{26}Al, ^{56}Co, ^{44}Sc) produced by supernovae, novae, or Wolf-Rayet stars, and γ-γ pair production in the vicinity of an accreting black hole. Each of these production sites and mechanisms has a unique spatial distribution and time history which will be reflected in the spatial distribution and time history of the annihilation radiation. The annihilation environment of the long-lived positrons will affect the observed spectral characteristics of the annihilation radiation in a manner which provides information on the physical characteristics of the annihilation medium. Measurements of the positron annihilation radiation thus provides a unique tool for both probing the energetic processes in the galaxy and for studying the interstellar medium (see, e.g. Ramaty & Lingenfelter, 1994, for a recent review).

The current work reports measurements of the longitude distributions of the 0.511 MeV line and the 3-photon positronium continuum components of the annihilation radiation, and the positronium fraction, in the galactic plane using a subset of the OSSE observations which was optimized for measurement of the positronium continuum.

2. Observation and data analysis

The OSSE instrument comprises four identical and independently orientable NaI(Tl)-CsI(Na) phoswich spectrometers, each of which has an aperture of $\sim 3.8°$ by 11.4° full-width at half-maximum (FWHM) at 0.511 MeV defined by a passive tungsten slat collimator. The positronium observations reported here were conducted and processed in the manner described in the OSSE instrument description paper of Johnson et al. (1993).

Here we have used only the subset of the OSSE observations of the galactic plane which had the long direction of the collimator approximately aligned with the plane (position angle of $\sim 90°$). All four detectors were operated in a source/background chopping mode in which each detector alternately viewed the galactic plane region for two minutes and one of two background fields located roughly 10° on either side of the plane for two minutes.

Send offprint requests to: R. L. Kinzer

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **1996**	2. REPORT TYPE	3. DATES COVERED **00-00-1996 to 00-00-1996**
4. TITLE AND SUBTITLE **OSSE observations of positron annihilation in the galactic plane**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Research Laboratory,Code 7650,4555 Overlook Avenue, SW,Washington,DC,20375**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Observations at seven longitude positions satisfied these criteria. Two positions (0° and 25°) had two observations. Only those observations which also had the collimator directed toward the plane (~ 0° latitude) were used in spectral determinations in order to maximize the signal-to-background ratio from the narrow galactic plane.

As shown by Purcell et al. (1993; 1994), the measured spectra from the galactic center direction can be well-represented by a model comprising an annihilation radiation component consisting of a 2.5 keV FWHM line centered at 511 keV and a three photon orthopositronium continuum (Ore & Powell, 1949), plus an underlying power-law continuum (see Fig. 1). The 0.511 MeV line intensity reported there is not very sensitive to the continuum model used. However, because the positronium continuum component is affected significantly by the choice of continuum model, we have investigated a range of continuum models in order to best characterize the positronium component and the underlying continua. Because

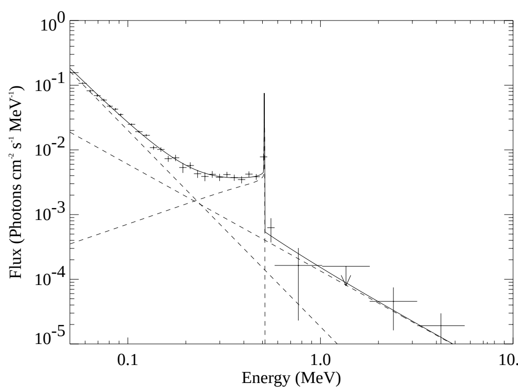

Fig. 1. Photon spectrum from one (VP 16) of two observations at 0° longitude. A fit of a 2 power-law continuum plus annihilation radiation model is shown by the solid line, with the fitted components indicated by dashed lines (power-law indices are ~ -3.0 and -1.65).

of an apparent flattening of the galactic plane continuum spectrum above a few hundred keV (e.g. Purcell et al., 1995; Strong et al., 1994), it is reasonable to represent the continuum with independent low and high energy components. The low energy continuum ($\leq$ 250 keV), which includes both cosmic-ray and discrete source contributions, is variable in intensity and spectral shape, especially near the galactic center where several highly variable point sources may contribute substantially. However, this low-energy continuum component is well represented in each of the observations used here by a simple power-law, with photon index ranging from -2.4 to -2.7. The high-energy continuum, a much harder spectrum expected to be dominated by cosmic ray effects (e.g. Strong et al. 1994), is not expected to be time-variable. OSSE does not have sufficient sensitivity to determine the continuum shape above about 500 keV in a single observation. However, it is possible to use measurements from other experiments at higher energies (see e.g. Gehrels & Tueller, 1993 for a review), including the recent COMPTEL measurements between 700 keV and 30 MeV (Strong et al., 1994), together with several OSSE measurements to define the spectral shape of the high energy continuum. This composite spectrum between ~ 600 keV and 50 MeV is well characterized by a power-law of photon index -1.65. This diffuse band of radiation along the plane has an uncertain width (e.g. Strong et al., 1994), particularly in the OSSE energy range, so that predictions of the intensity expected in the narrow OSSE collimators is uncertain. Given the above spectral shape, OSSE has sufficient sensitivity to define the overall spectral intensity of this component. At directions away from the center, the relative amplitude of this diffuse component is assumed to follow the galactic longitude intensity distribution of CO in the plane (eg. Strong et al., 1994; Dame et al. 1987).

Three of the continuum models considered here use this fixed high-energy component together with an independent low-energy continuum component described either by another power-law, a themal comptonization, or a thermal bremsstrahlung model. A fourth continuum model used a simple power-law over the full continuum range. These models all gave acceptable fits to the composite spectra at the seven longitudes considered here. The small differences in chi-squared probabilities cannot determine the "best" model, particularly in the critical 200 - 500 keV positronium continuum range where the statistical precision of the data decreases with energy. The two power-law and the thermal comptonization plus high energy power-law continua models generally have the highest over-all chi-squared probability and best represent the data in this critical region and at high energies. The two power-law model was used to obtain the intensity distributions discussed below.

3. Experimental Results

3.1. Galactic longitude distribution

Fig. 2 shows the fitted intensity values for the 3-photon positronium continuum as a function of the galactic longitude of the collimator axis during the observations. The OSSE collimator smooths the input from this distributed source. A simple empirical model, which assumes a one-dimensional Gaussian shape for the central longitude bulge component and a longitude shape following the CO gas distribution (Dame et al. 1987) for the broad galactic disk component underlying the bulge, can represent the data well (other disk models are not excluded by the data). The latter has the form expected from the decay of positrons produced in the decay of galactic ^{26}Al (e.g. Mahoney et al 1984, Share et al. 1985), which was

observed recently by COMPTEL (Diehl et al. 1995) to roughly follow the galactic CO distribution. By folding this two-component model through the detector response (solid line in Fig 2), the best-fit longitude width of the central Gaussian component was determined to be $\sim 11°$ FWHM. The intensity of the disk component, not well-constrained by the data, is $\sim 15\%$ of the integral intensity between 40° and 320° longitude. Fig. 3 shows a similar distribution of the narrow 0.511 MeV line intensities which were measured simultaneously with the positronium continuum values. Its shape is well-represented by the same model shape (solid line, see Fig 2). This suggests that the two components have a common spatial origin, as expected, and is consistent with a large fraction of the observed annihilation radiation occuring via positronium formation. We have added the two component intensities to obtain a statistically improved distribution. This is shown in Fig. 4, along with a normalized version of the detector-convolved positronium continuum model curve (solid line). Good agreement with the total annihilation radiation distribution is apparent. The input model, normalized so that the input and convolved model curves have the same area between 40° and 320° longitude, is shown as a dashed line. The galactic longitude bulge and extended disk components of the input model are shown by the dash-dotted and the long-dashed lines, respectively. Units for the input model components are arbitrary.

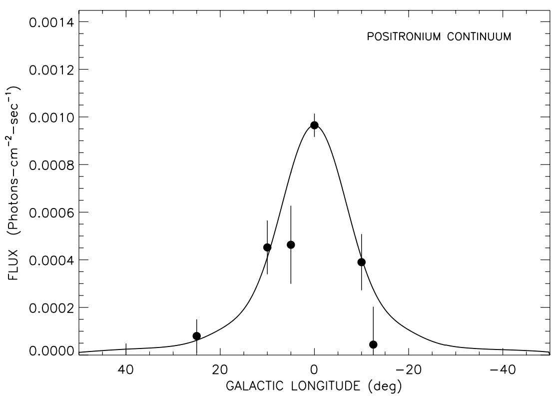

Fig. 2. Galactic longitude distribution of the 3-photon positronium continuum. Solid line is the convolved best-fit model comprising an $\sim 11°$ FWHM Gaussian in galactic longitude at the center plus a disk component following the CO distribution.

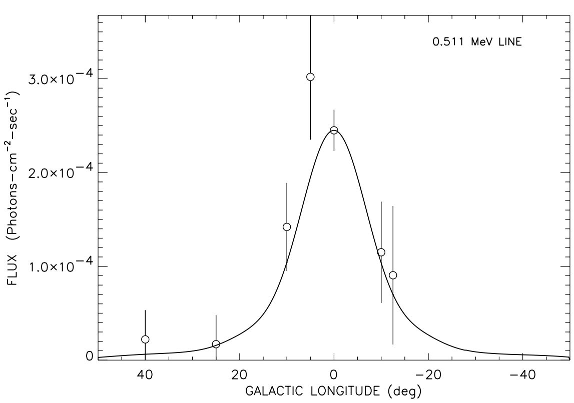

Fig. 3. Longitude distribution of the 0.511 MeV line intensity, with a normalized overlay of the detector-convolved model obtained for the 3-photon continuum distribution (Fig. 2).

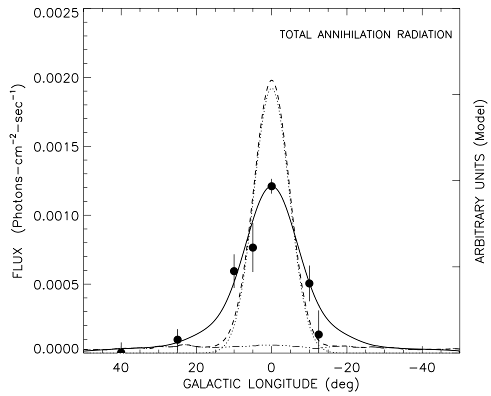

Fig. 4. Sum of the 3-photon continuum and 0.511 MeV line distributions, with an area-normalized version of the convolved 3-photon continuum fitted model (Fig. 2). The dashed line is the input model. The gaussian component is indicated by a dotted line, and the broad disk component by a dashed-dotted line.

3.2. Positronium Fraction

Two independent measurements were made at 0° longitude, each of which have high statistical significance and a strong annihilation radiation signal; one is shown in Fig. 1. These two observations provide our best estimates of the positronium fraction. They yield consistent estimates of the positronium fraction even though their low-energy continua differ by a factor of ~ 1.6 at 100 keV due to variable discrete source contributions. Because the 3-photon continuum intensity is sensitive to the low energy continuum model used, it is possible to further investigate the accuracy of the derived positronium fraction by comparing the range of positronium fraction values, f, obtained with the four different continuum models described above, where (e.g. Brown & Leventhal 1987):

$$f = \frac{2.0}{2.25 \times (f_{511}/f_{pos}) + 1.5}$$

(f_{511} and f_{pos} are the 0.511 MeV line and positronium 3-photon continuum fluxes, respectively). A value of f=0 indicates that none of the positrons decay through the positronium channel; f=1 indicates that 100% do.

The lowest estimate of f, 0.97 ± 0.03, is given by the two power-law continuum model, which provides good fits to the overall spectra. The thermal comptonization plus power-law continuum model, which provides equally good fits over the full spectral range, gives $f = 1.02 \pm 0.03$, consistent with the maximum possible value of 1.0. The single power-law continuum model, which does not represent the data as well, gives $f = 0.98 \pm 0.03$. The thermal bremsstrahlung plus power-law continuum model, which provides the poorest fits, gives a value $f = 1.07 \pm 0.03$, suggesting that this model incorrectly models the positronium and underlying continuua. Thus, the OSSE measurements indicate a high positronium fraction (between 0.94 and 1.0) in the galactic center direction.

4. Discussion

The current measurements provide, for the first time, a quantitative measure of the galactic distribution of both the 0.511 MeV line and the 3-photon continuum components of the annihilation radiation with angular discrimination sufficiently narrow to resolve the gross angular structure of the distribution. Within the statistical accuracy of the observations, the line and continuum components are distributed along the plane identically about the galactic center (Figs. 2 & 3). The narrow one-dimensional peak (an $\sim 11°$ FWHM gaussian), symmetrical in longitude about the center, can account for the bulk of the annihilation radiation toward the center; a much weaker disk component extending as far as 25° from the center is consistent with the observations. This longitude dimension for the bulge component is consistent with the narrower spheroidal bulge suggested by Purcell et al. (1994) for the 0.511 Mev line distribution, provided the bulge is slightly elongated in the longitude direction. Contributions from one or more compact sources, such as a black hole, at or near the center with total annihilation radiation (line plus continuum) intensities of up to $\sim 4 \times 10^{-4}$ photons cm^{-2} sec^{-1} (2σ upper limit) are compatible with the observed distribution. Greater contributions from a central source would be detectable. This limit is consistent with that found by Purcell et al. (1993; 1994) for the 0.511 MeV line obtained with the much larger OSSE data set comprising observations at all collimator position angles.

If the emission from the galactic center region were dominantly from compact objects, f would be expected to be lower than 0.9, and possibly as low as 0.5 (e.g. Bussard, Ramaty, & Drachman 1979; Zurek, 1985; Guessoum, Ramaty & Lingenfelter, 1991). The lowest estimate of f, 0.97 ± 0.03, from the current OSSE observations argues against a large contribution from dense regions associated with compact objects.

The observed annihilation radiation bulge component differs from previously observed high-energy radiation distributions, and thus implies a unique origin for this radiation. The dominant $\sim 11°$ FWHM bulge component, with a positronium fraction approaching 1.0, is likely to arise from positrons distributed in the interstellar medium which originated from a population of discrete sources associated with the galactic bulge. The most likely candidates are Type Ia and Ip supernovae, which can produce adequate amounts of ^{56}Ni and ^{44}Ti to explain the observations (e.g. Colgate, 1970; Chan & Lingenfelter, 1993). The $\sim 15\%$ contribution to the flux from an extended disk component (Fig. 4) is consistent with the $\sim$ 8 -18% contribution expected (Chan & Lingenfelter, 1993) from the observed distribution of ^{26}Al in the galaxy.

If annihilation occurs predominantly in the gaseous interstellar medium, then positronium annihilation is expected to account for the bulk of the emitted radiation, with an expected positronium fraction depending on the annihilation environment. The positronium fraction in a cold neutral medium was measured in the laboratory to be 0.897 ± 0.003 in H_2 (Brown, Leventhal and Mills, 1986) and was calculated to be 0.935 in H_2 and 0.945 in H (Bussard, Ramaty, & Drachman 1979). A positronium fraction of 0.97 implies annihilation in a warm neutral medium ($\sim$ 6000 - 7000 K), or in a warmer (up to $\sim 10^5$ K) ionized medium (Bussard, Ramaty, & Drachman 1979).

References

Brown, B., Leventhal, M., & Mills, A. 1986, Phys. Rev. A, 33, 2281

Brown, B., & Leventhal, M. 1987, ApJ, 319, 637

Bussard, R., Ramaty, R.,& Drachman,R. 1979, ApJ, 228, 928

Chan, K. & Lingenfelter, R. 1993, ApJ, 405, 614

Colgate, S. 1970, Ap Sp Sci, 8, 457

Dame, T. et al. 1987, ApJ, 322, 706

Diehl, R. et al. 1995, A&A, 298, 445

Gehrels, N. & Tueller, J. 1993, ApJ, 407, 597.

Guessoum, N., Ramaty,R.,& Lingenfelter,R. 1991, ApJ, 378, 170

Johnson, W. N., & Haymes, R. C. 1973, ApJ, 184, 103

Johnson, W. N., et al. 1993, ApJ Suppl., 86, 693

Mahoney, W., Ling, J., Wheaton, W., & Jacobson, A. 1984, ApJ, 286, 578

Ore, A. & Powell, J. 1949, Phys. Rev., 75, 1696

Purcell, W., Grabelsky, D., Ulmer, P., Johnson, W., Kinzer, R., Kurfess, J., Strickman, M., & Jung, G. 1993, ApJ, 413, L85.

Purcell, W., et al. 1994, in The 2nd Compton Symp., ed. C. Fichtel, N. Gehrels, & J. Norris (New York:AIP), 403

Purcell, W., et al. 1995, These Proceedings

Ramaty, R. & Lingenfelter, R. 1994, in High Energy Astrophysics, ed J. Matthews (Singapore: world Scientific), 1

Share, G. H., Kinzer, R. L., Kurfess, J. D., Forrest, D. J., Chupp, E. L., & Rieger, E. 1985, ApJ, 292, L61

Strong, A. W., et al. 1994, A&A, 292, 82

Zurek, W. H. 1985, ApJ, 289, 603

This article was processed by the author using Springer-Verlag LTEX A&A style file *L-AA* version 3.